Effect of faults and fractures on oilfield flow rate data: long-range correlations in a complex system

Ian Main, Lun Li, Thomas Leonard & Orestis Papasouliotis
University of Edinburgh

Kes Heffer
Reservoir Dynamics Ltd.

Xing Zhang & Nick Koutsabeloulis

Schlumberger

Results of ITF (Aberdeen) 'Coffers' project
Data provided by Statoil, sponsored by BP, Shell, Statoil, Conoco-Phillips, Maersk, Total, Hess, BG group, DTI.

References

- Main, I.G., L. Li, K. Heffer, O. Papasouliotis & T. Leonard (2006). Long-range, critical-point dynamics in oilfield flow rate data, *Geophys. Res. Lett*. 33, L18308, doi:10.1029/2006GL027357.

- Heffer, K., X. Zhang, N. Koutsabeloulis, I. Main and L. Li (2007). Identification of activated (therefore potentially conductive) faults and fractures through statistical correlations in production and injection rates and coupled flow-geomechanical modelling, *Society of Petroleum Engineers*, paper no. 107164, 9pp.

In press

- Main, I.G., L. Li, K. Heffer, O. Papasouliotis, T. Leonard, N. Koutsebaloulis & X. Zhang (2007). The Satistical reservoir model: Calibrating faults and fractures, and predicting reservoir response to water flood, in Jolley, S. (ed.), *Geol. Soc. Lond., special volume on Complex Reservoirs*.

- Zhang, X., N. Koutsebaloulis, K. Heffer, I. Main and L. Li (2007). Analysis of geomechanics and production data for critically-stressed reservoirs – generic characteristics and application to Gullfaks, in Jolley, S. (ed.), *Geol. Soc. Lond., special volume on Complex Reservoirs*.

Preamble: triggering phenomena

- Earthquake-earthquake
  (Marsan et al, Huc & Main,
  Helmstetter & Sornette, Felzer & Brodsky)
  - static or dynamic?
- Pore pressure-earthquake
  (Segall, Kohl & Megel)
  - poroelasticity and induced seismicity
- Earthquake-pore pressure
  (Doan & Cornet)
  - borehole response
- Pore pressure-pore pressure?
  (Main et al, Heffer et al)
  - flow rate-flow rate

=> Reservoir modelling


Monarch to get a face-lift

Big spender

Earthquake modelling technique provides reservoir pointers

IN THE PIPELINE

The COFFERS project has made excellent progress in developing a methodology to model fluid flow in complex reservoirs. It will eventually be possible for operating companies to incorporate the software within their existing workflows to help optimise production strategies

DUNCAN ANDERSON, ITF SUBSURFACE TECHNOLOGY MANAGER

Outline

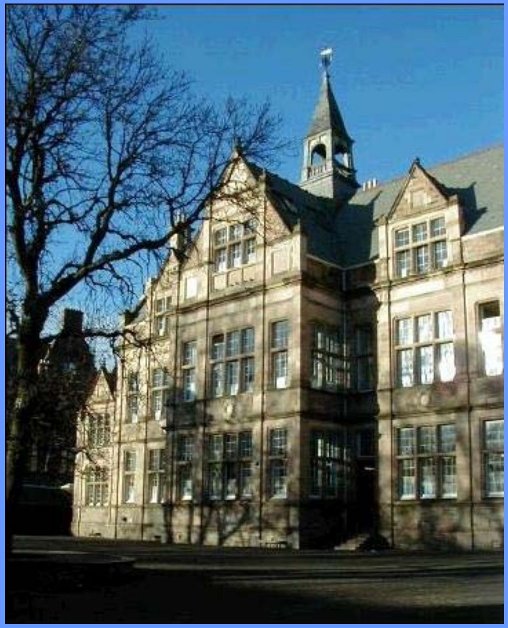
- Background concepts: statistical forecasting, parsimony in model fitting, principal component analysis, geo-mechanics and permeability
- The statistical reservoir model
- Application to the Gullfaks field, North Sea
- Application of a geo-mechanical model to the same field
- Conclusions

Statistical forecasting
Example: Buying a house

$\boxed{\pounds\pounds = ??}$

Buying a house: A statistical model

$$\text{££} = w_1 x_1 + \ldots$$



Buying a house: A statistical model

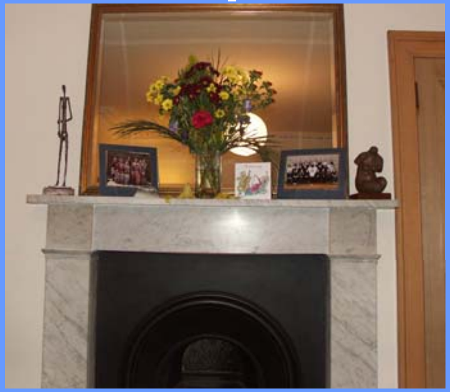
Local School?

$$\boxed{\pounds\pounds = w_1 x_1 + w_2 x_2 + \ldots}$$

Buying a house: A statistical model

Local School?   South Facing Garden?

$$\pounds\pounds = w_1 x_1 + w_2 x_2 + \ldots + w_i x_i + w_{i+1} x_{i+1} + ..$$



Buying a house: A statistical model

Local School? South Facing Garden?

$$\pounds\pounds = w_1 x_1 + w_2 x_2 + \ldots + w_i x_i + w_{i+1} x_{i+1} + \ldots w_n x_n$$

Period features?

Buying a house: A statistical model

$w_i, i = 1, n$ Define a set weights

Local School? South Facing Garden?

$$\pounds\pounds = w_1 x_1 + w_2 x_2 + \ldots + w_i x_i + w_{i+1} x_{i+1} + \ldots w_n x_n$$

Period features? Kitchen Sink

SIGNAL NOISE

A History of Parsimony

- ***William of Ockham*: "That which is accomplished by fewer (assumptions) is accomplished in vain with more"**
- ***Carl Friedrich Gauss***

$$\boxed{\sigma^2 = \sum_{i=1}^{n}[y_i - \hat{\gamma}(x_i)]^2 / (n-p)}$$

- ***Hirotsugu Akaike***

$$\boxed{AIC = n \ln\left\{\sum_{i=1}^{n}[y_i - \hat{\gamma}(x_i)]^2 / n\right\} - p}$$

n = no. of data points
p = no. of parameters

Information vs. goodness of fit

$$y = 1 + x - x^2 : \ \sigma^2 = 1$$

$$BIC = n \ln\left\{ \sum_{i=1}^{n} [y_i - \hat{\gamma}(x_i)]^2 / n \right\} - p[\ln(n/2\pi)]$$

m	3	4	5	6	7	8	9
AIC	0	0.705	0.120	0.078	0.044	0.030	0.023
BIC	0	0.841	0.080	0.046	0.019	0.009	0.005

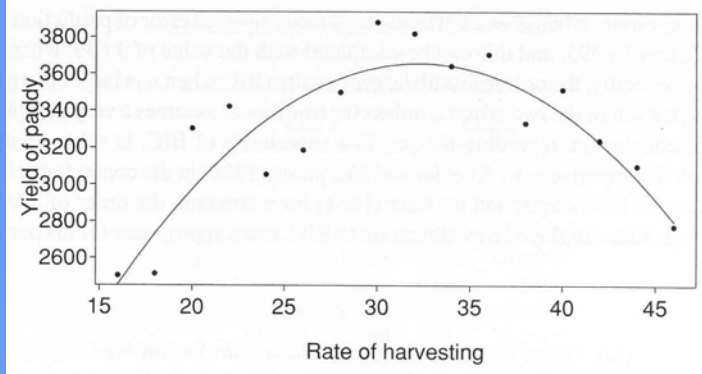


Figure 1.2.8. Fitting a quadratic regression curve.

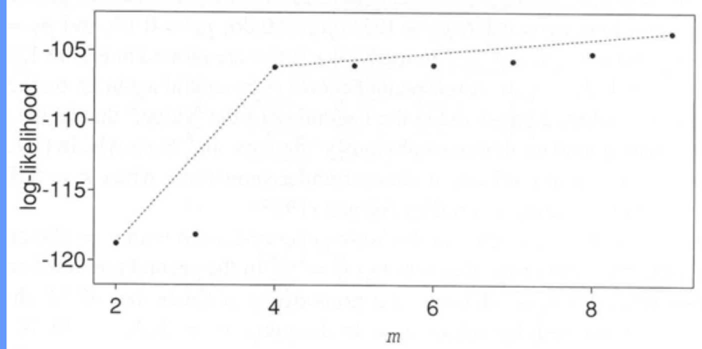


Figure 1.2.9. Log-likelihood plot for polynomial regression.

Principal component analysis
Example: stress rotation

$$\boxed{\begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{bmatrix} = R^T(\theta,\phi) \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix} R(\theta,\phi)}$$

$$\boxed{\sigma_1 \geq \sigma_2 \geq \sigma_3}$$

Second Example: mineral prospecting

Table *1.1. The raw data matrix for the lead–zinc prospecting problem*

				Geological properties									
			Causes	Mg in calcite	Fe in sphalerite	Na in muscovite	Sulfide	Crystal size of carbonates	Spacing of cleavage	Elongation of ooliths	Tightness of folds	Vein material per m^2	Fractures per m^2
			T	0.95	0.75	0.75	0.33	−0.20	0.05	0.20	0.10	0.00	0.05
			D	0.00	0.10	0.20	0.33	0.60	0.95	0.70	0.85	0.10	0.25
			P	0.05	0.15	0.05	0.34	0.60	0.00	0.10	0.05	0.90	0.70
Locality	*T*	*D*	*P*	Data matrix									
1	121	21	46	117.25	99.75	97.25	62.50	16.00	26.00	43.50	32.25	43.50	43.50
2	96	35	42	93.30	81.80	81.10	57.51	27.00	38.05	47.90	41.45	41.30	42.95
3	78	54	49	76.55	71.25	71.75	60.22	46.20	55.20	58.30	56.15	49.50	51.70
4	63	51	49	62.30	59.70	59.90	54.28	47.40	51.60	53.20	52.10	49.20	50.20
5	42	44	44	42.10	42.50	42.50	43.34	44.40	43.90	43.60	43.80	44.00	43.90
6	39	26	54	39.75	39.95	37.15	39.81	40.20	26.65	31.40	28.70	51.20	46.25
7	52	36	52	52.00	50.40	48.80	46.72	42.40	36.80	40.80	38.40	50.40	48.00
8	67	46	54	66.35	62.95	62.15	55.65	46.60	47.05	51.00	48.50	53.20	52.65
9	90	37	51	88.05	78.85	77.45	59.25	34.80	39.65	49.00	43.00	49.60	49.45
10	108	27	61	105.65	92.85	89.45	65.29	31.20	31.05	46.60	36.80	57.60	54.85
11	112	33	59	109.35	96.15	93.55	67.91	32.80	36.95	51.40	42.20	56.40	55.15
12	91	38	59	89.40	80.90	78.80	62.63	40.00	40.65	50.70	44.35	56.90	55.35
13	76	39	54	74.90	69.00	67.50	56.31	40.60	40.85	47.90	43.45	52.50	51.35
14	63	30	51	62.40	57.90	55.80	48.03	36.00	31.65	38.70	34.35	48.90	46.35
15	43	19	55	43.60	42.40	38.80	39.16	35.80	20.20	27.40	23.20	51.40	45.40
16	68	16	42	66.70	58.90	56.30	42.00	21.20	18.60	29.00	22.50	39.40	36.80
17	77	27	41	75.20	66.60	65.20	48.26	25.40	29.50	38.40	32.70	39.60	39.30
18	93	37	43	90.50	79.90	79.30	57.52	29.40	39.80	48.80	42.90	42.40	44.00
19	102	47	48	99.30	88.40	88.30	65.49	36.60	49.75	58.10	52.55	47.90	50.45
20	120	36	46	116.30	100.50	99.50	67.12	25.20	40.20	53.80	44.90	45.00	47.20

Map of first three principal components

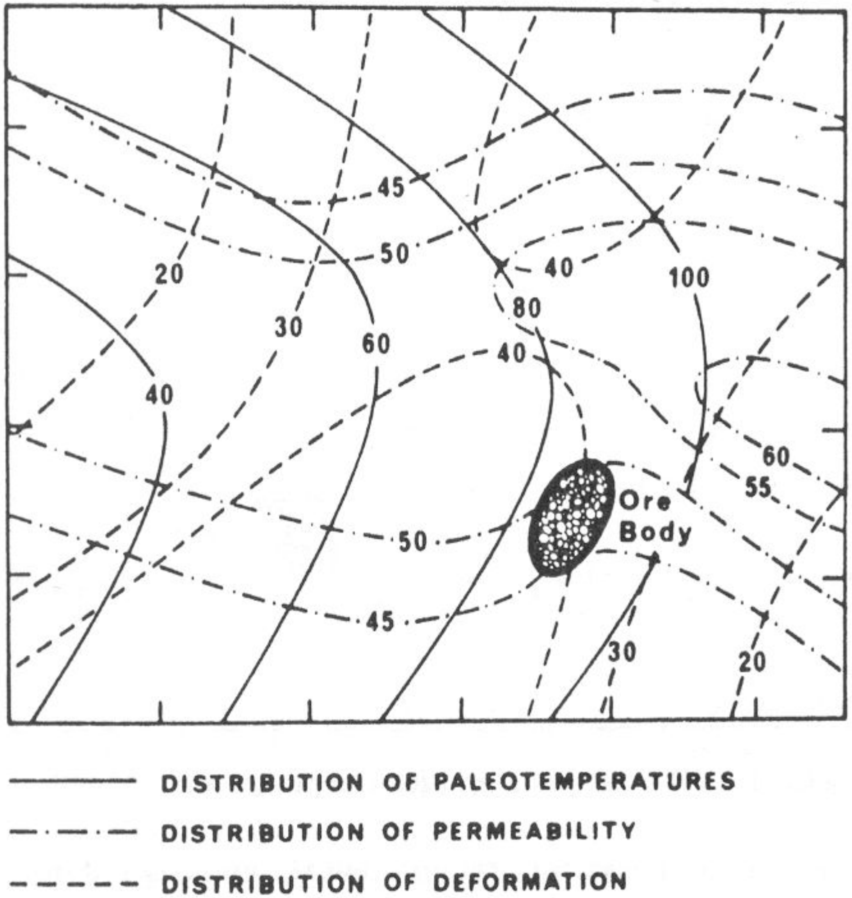
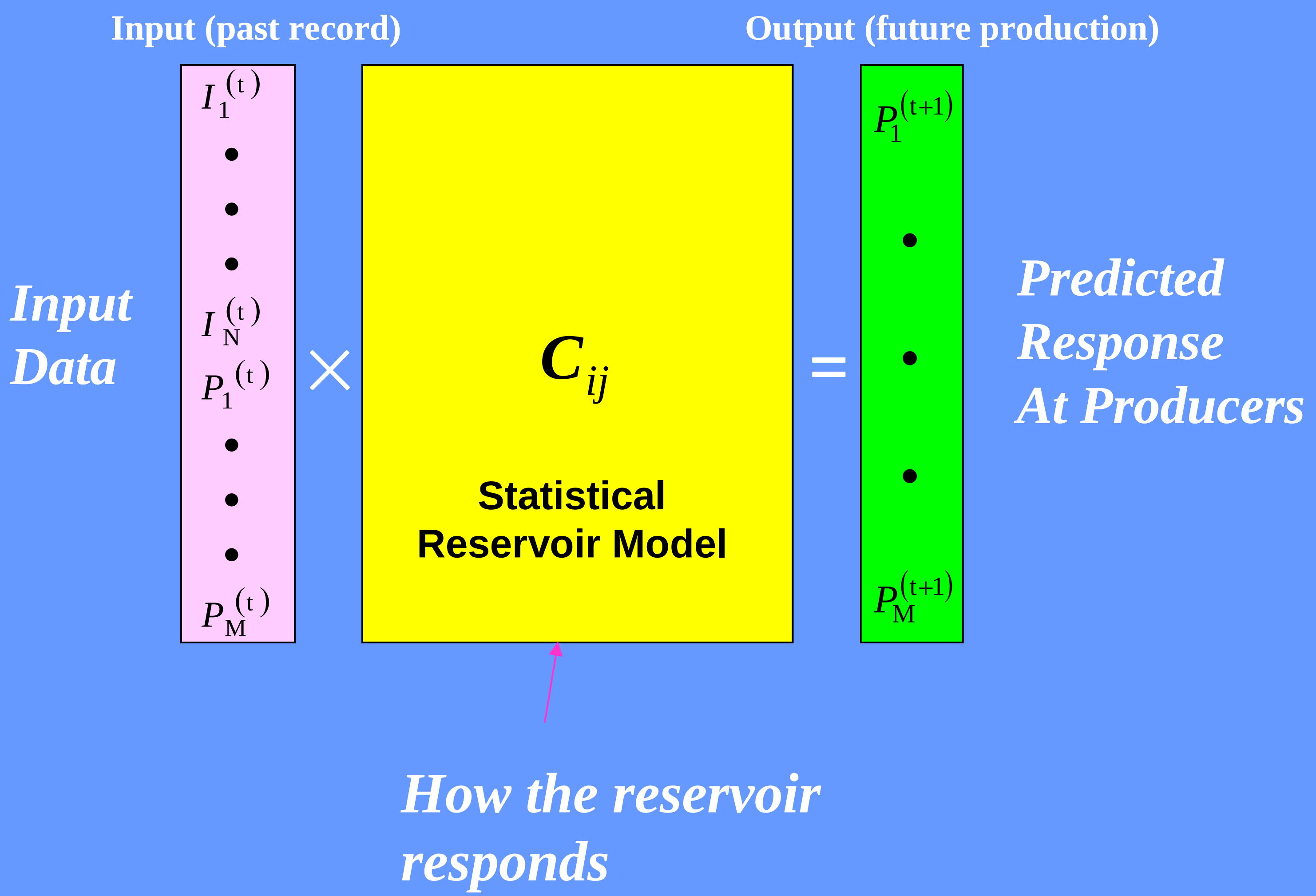
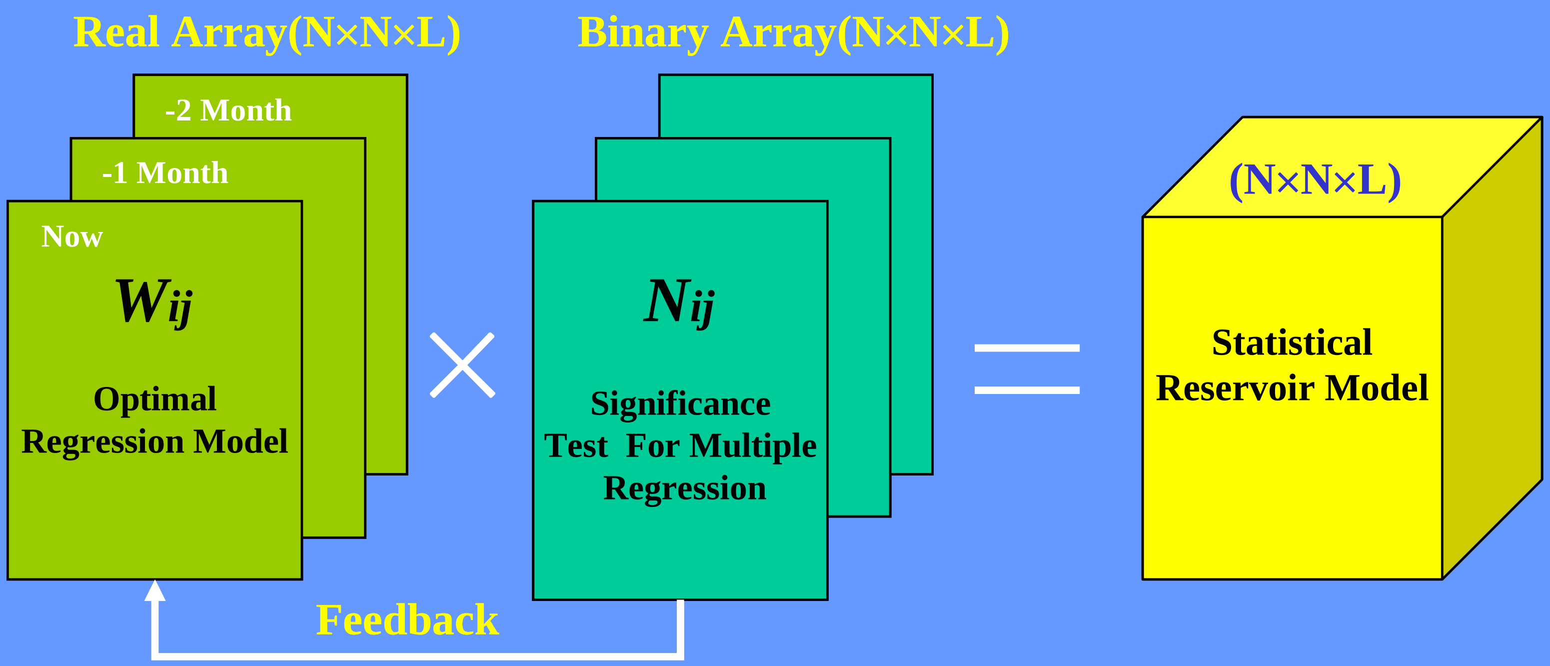


Figure 1.2. Distribution of controls imposed at the locations of the samples.

The statistical Reservoir Model

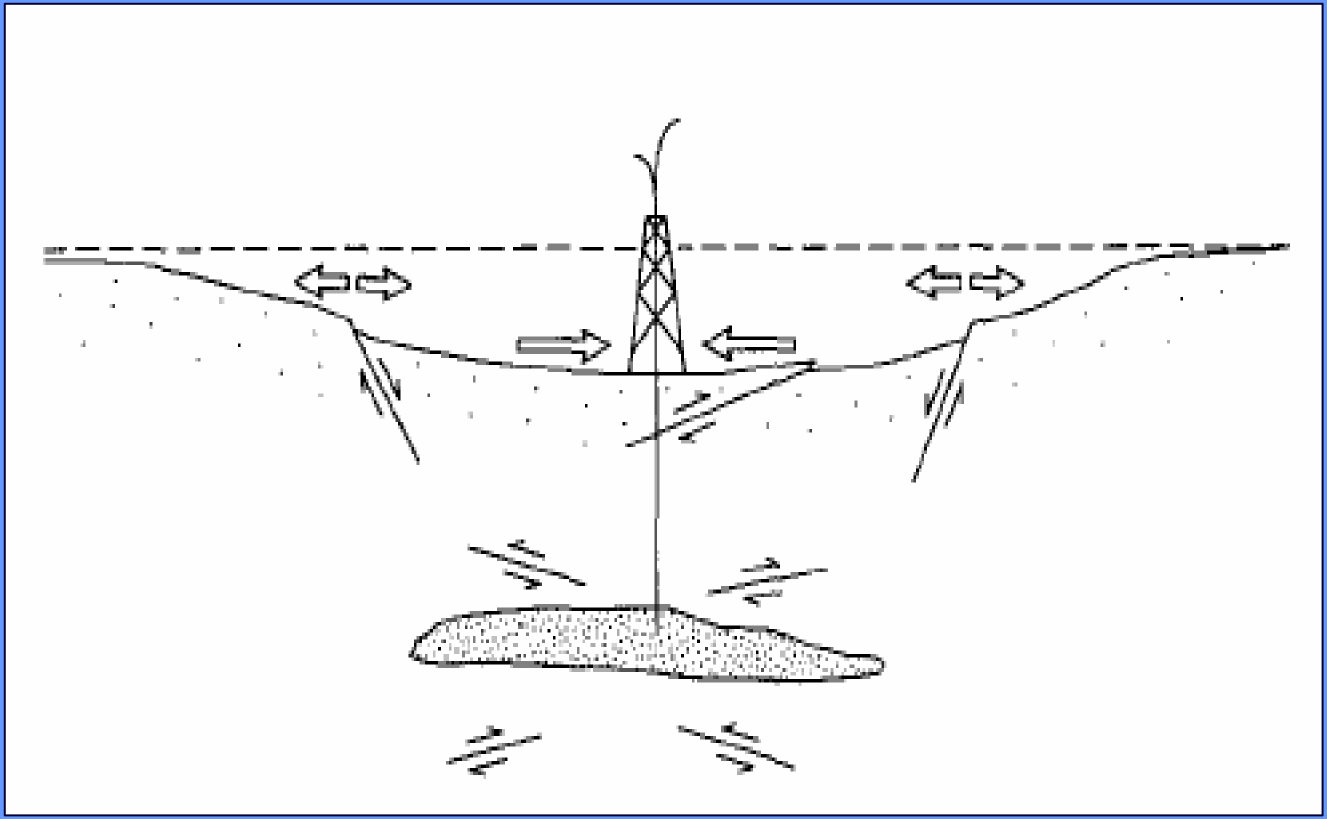


Separating signal from noise: a parsimonious model



UK patent application 0524134.4 filed 26/11/2005

Geo-mechanical model: long-range poro-elasticity

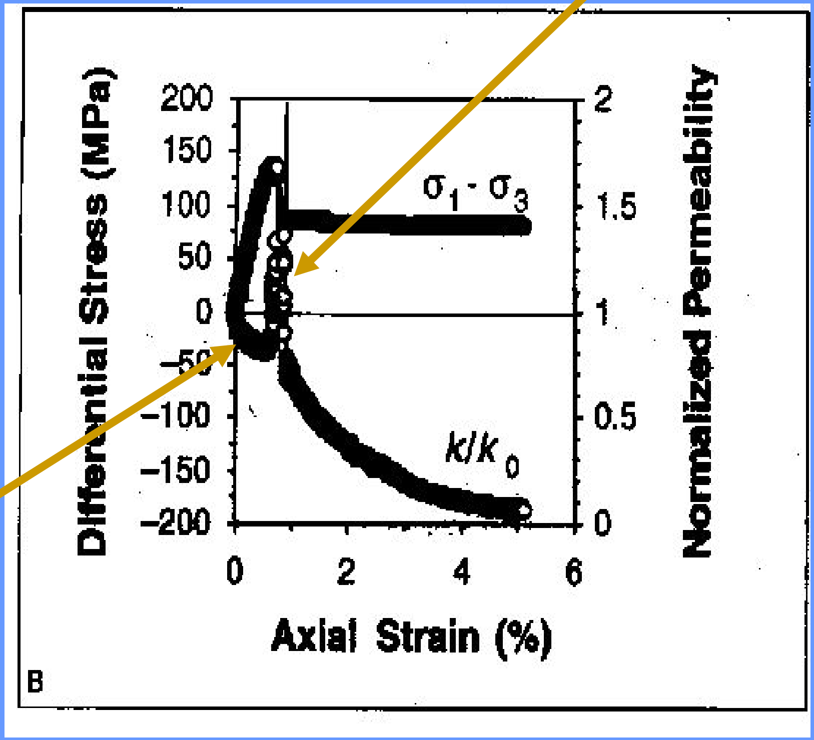


Deformation and faulting associated with fluid extraction (*Segall*, 1989)

Geo-mechanical model: Permeability response to deformation

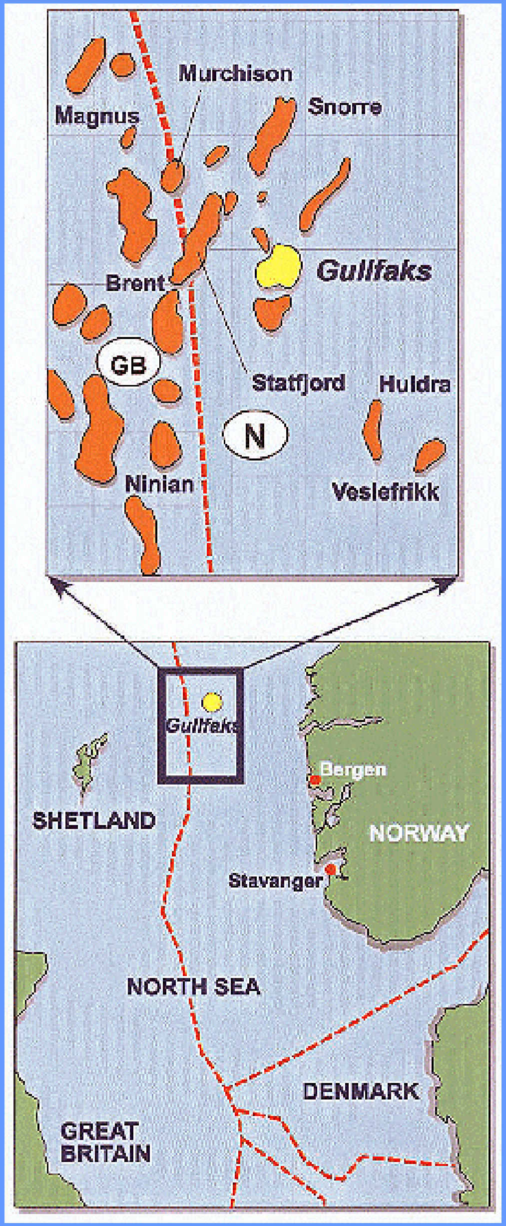
Non-linear, near critical

Linear

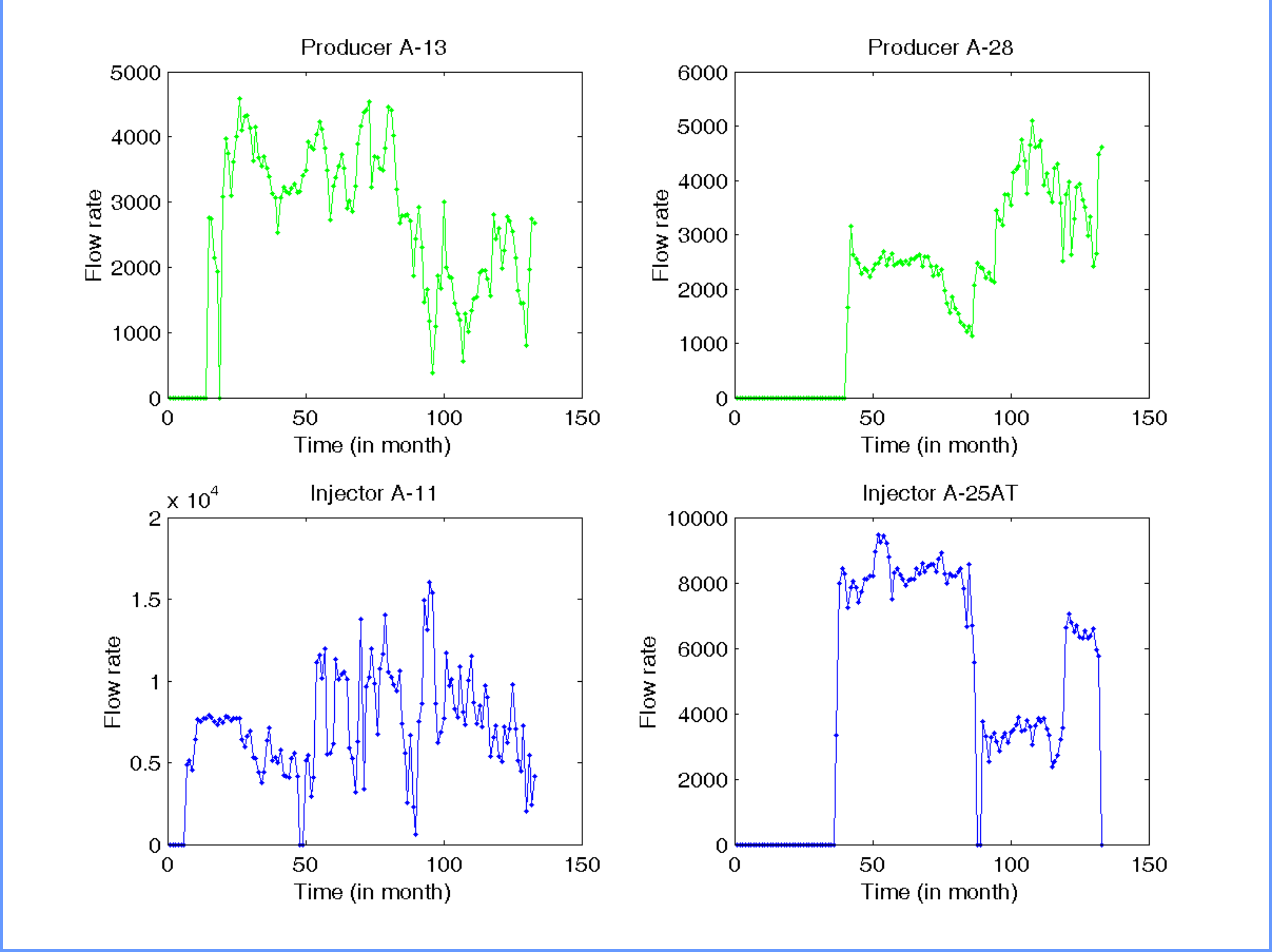


Test case: The Gullfaks field (after *Arild Hesjedal*)

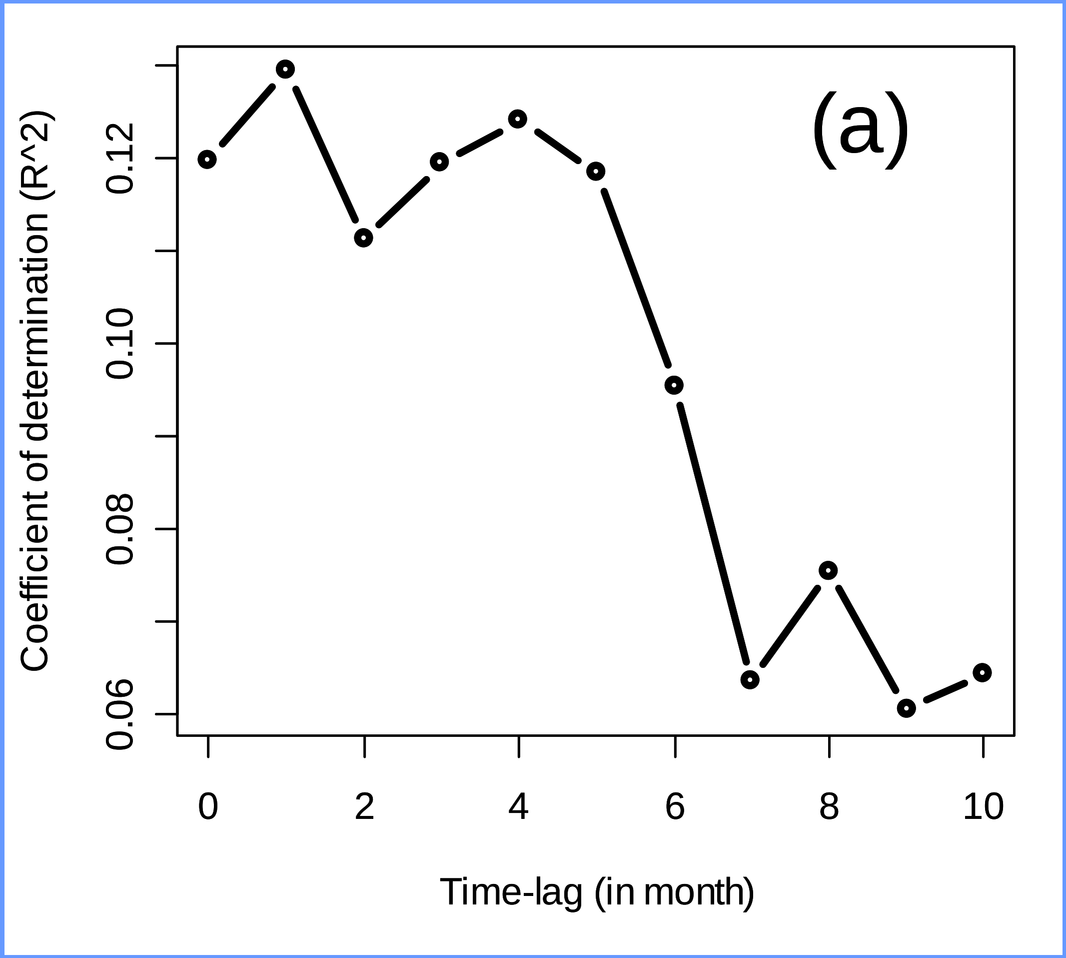
- Complex, faulted reservoir
- In block 34/10 in the northern part of the Norwegian North Sea.
- Total of 133 months data 1986-1997
- 106 platform wells (79 producers +27 injectors >24 months) used
- Data provided free for academic use



Time series for flow rate

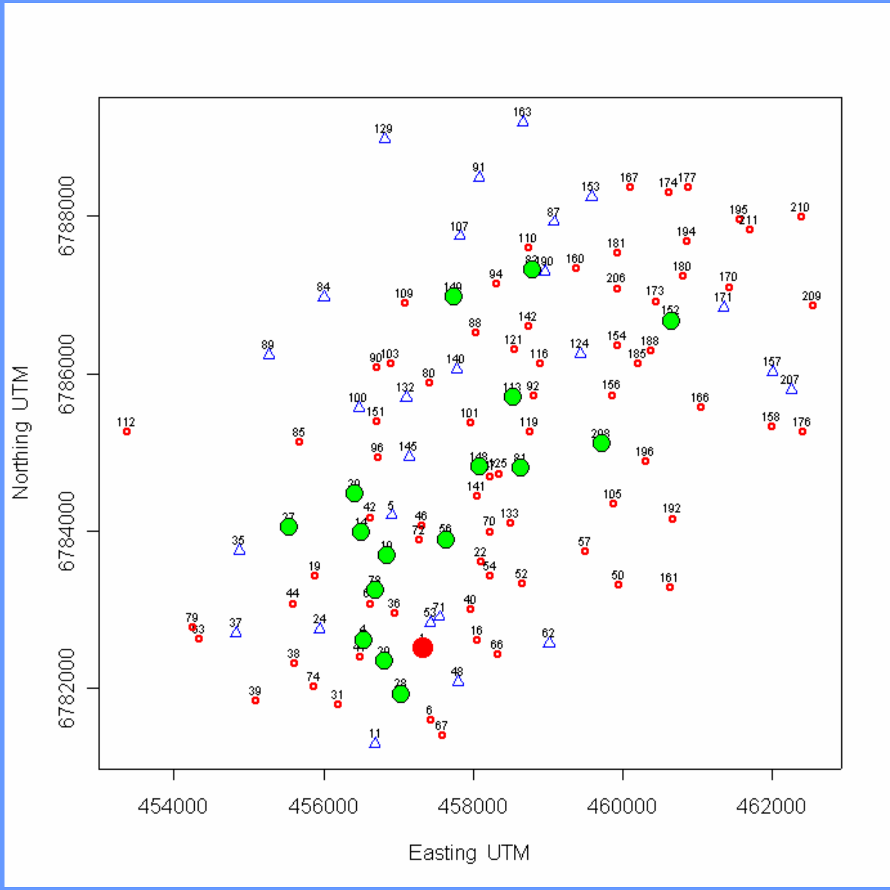


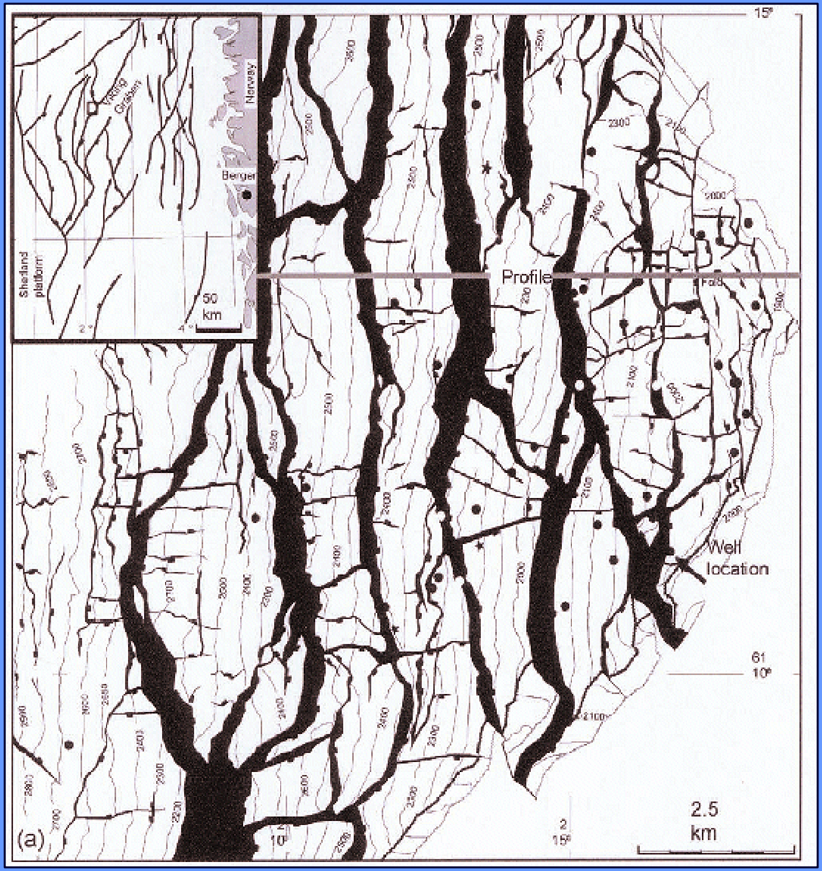
Cross-correlation function



'Direct' and time-delayed effects seen over a few months

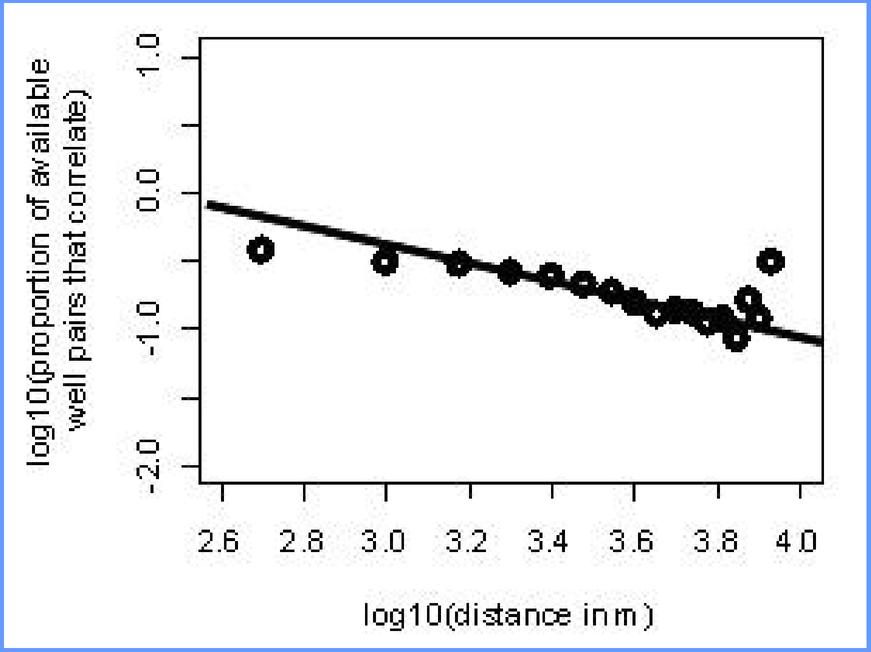
Significantly correlated wells



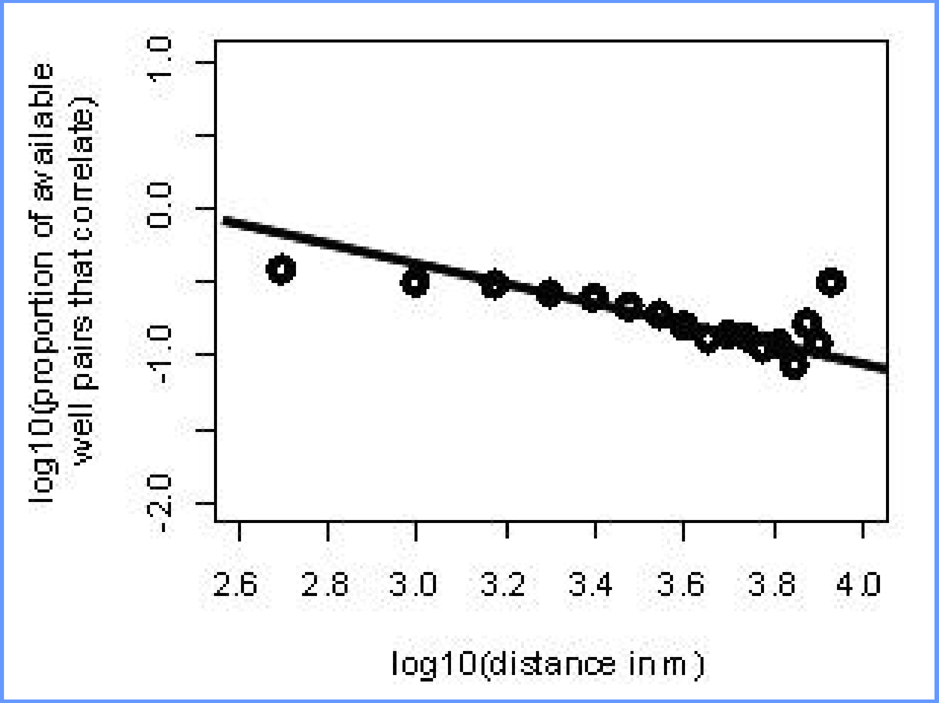


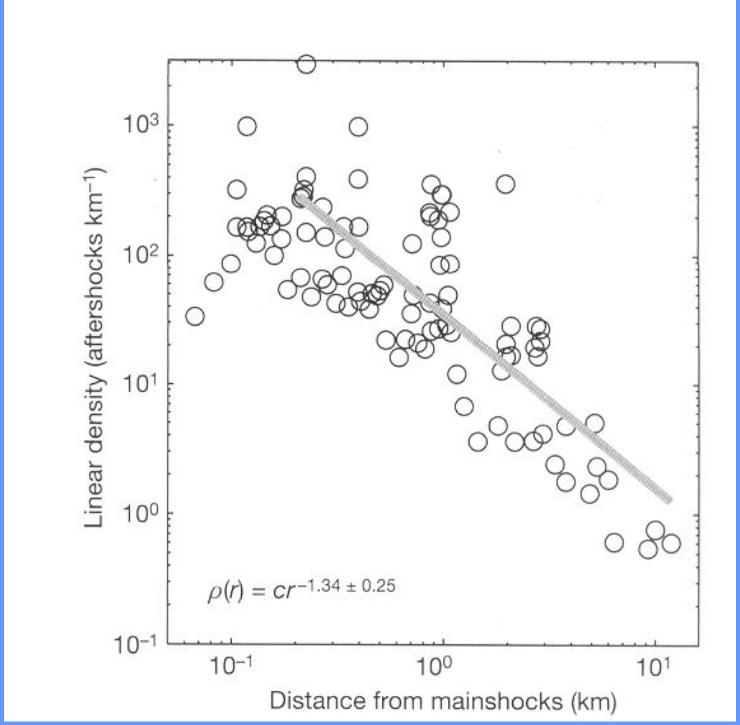
Fault map of the Gullfaks Field (*Fossen et al.*, 1998).

Correlation function for significantly correlated wells



Correlation function for significantly correlated wells

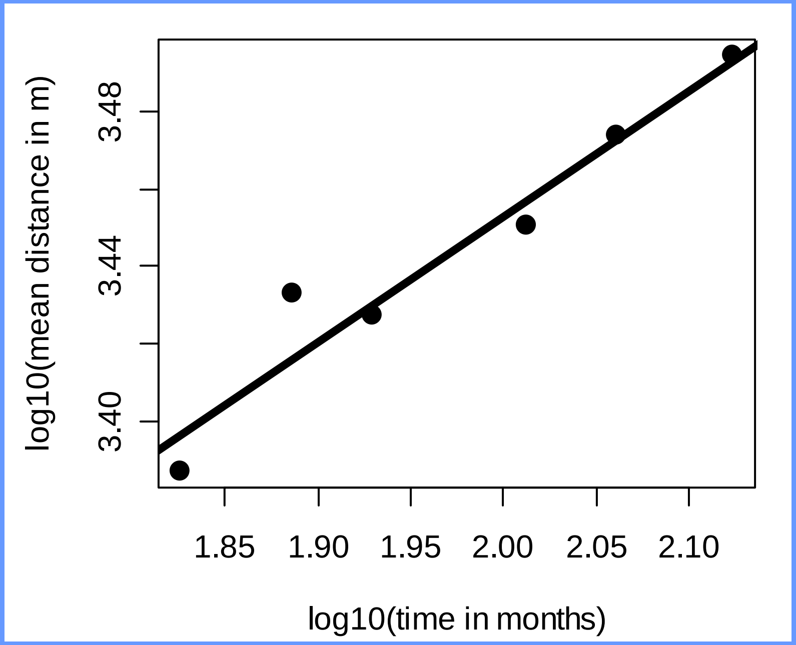




Flow rate correlations

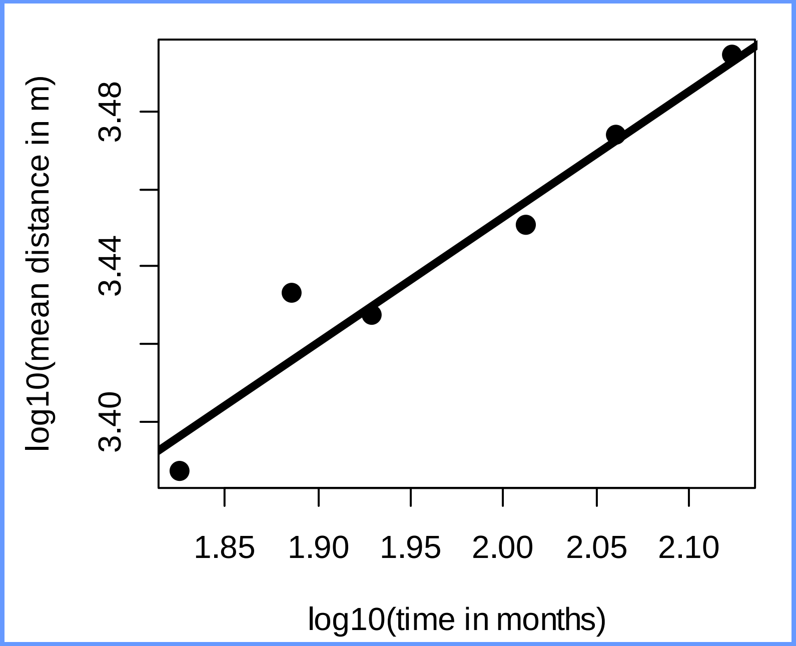
Earthquake aftershocks
(Felzer & Brodsky, 2006)

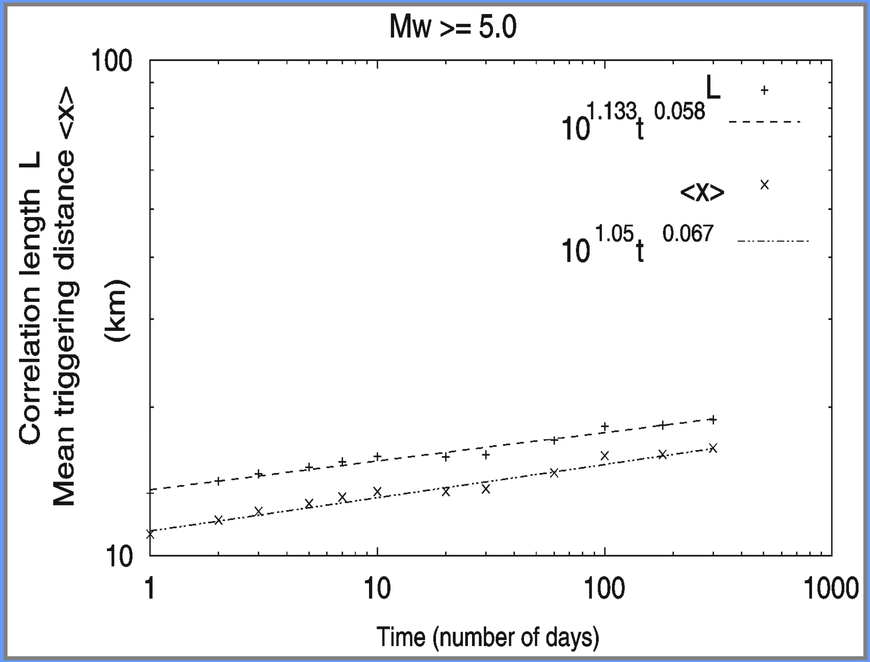
Anomalous (slow) diffusion



<x>~$t^{0.3}$ for significantly correlated well pairs

Anomalous (slow) diffusion

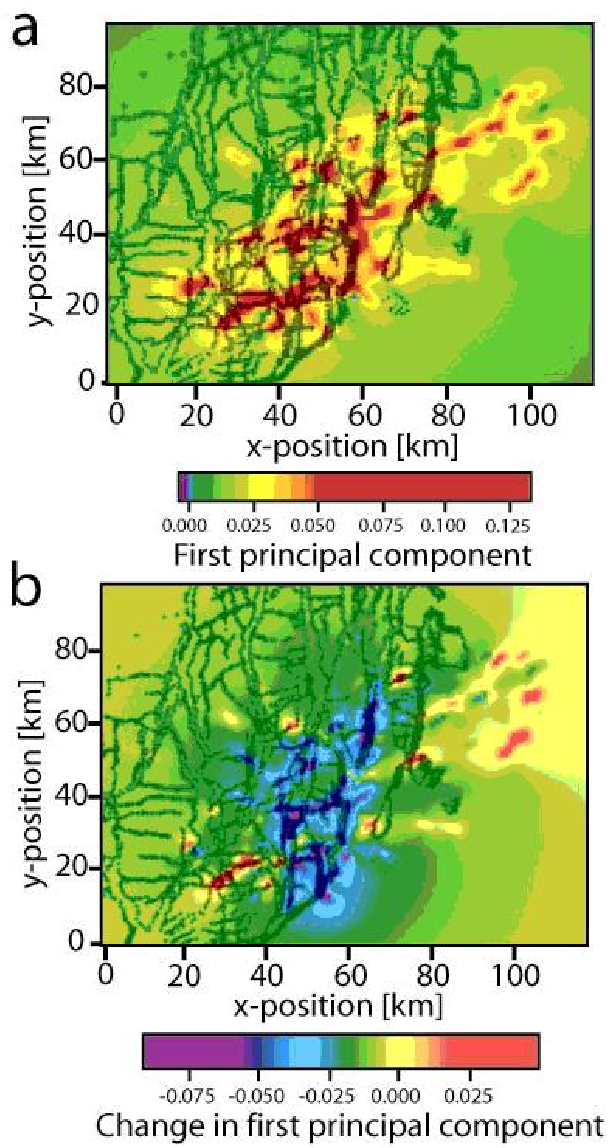




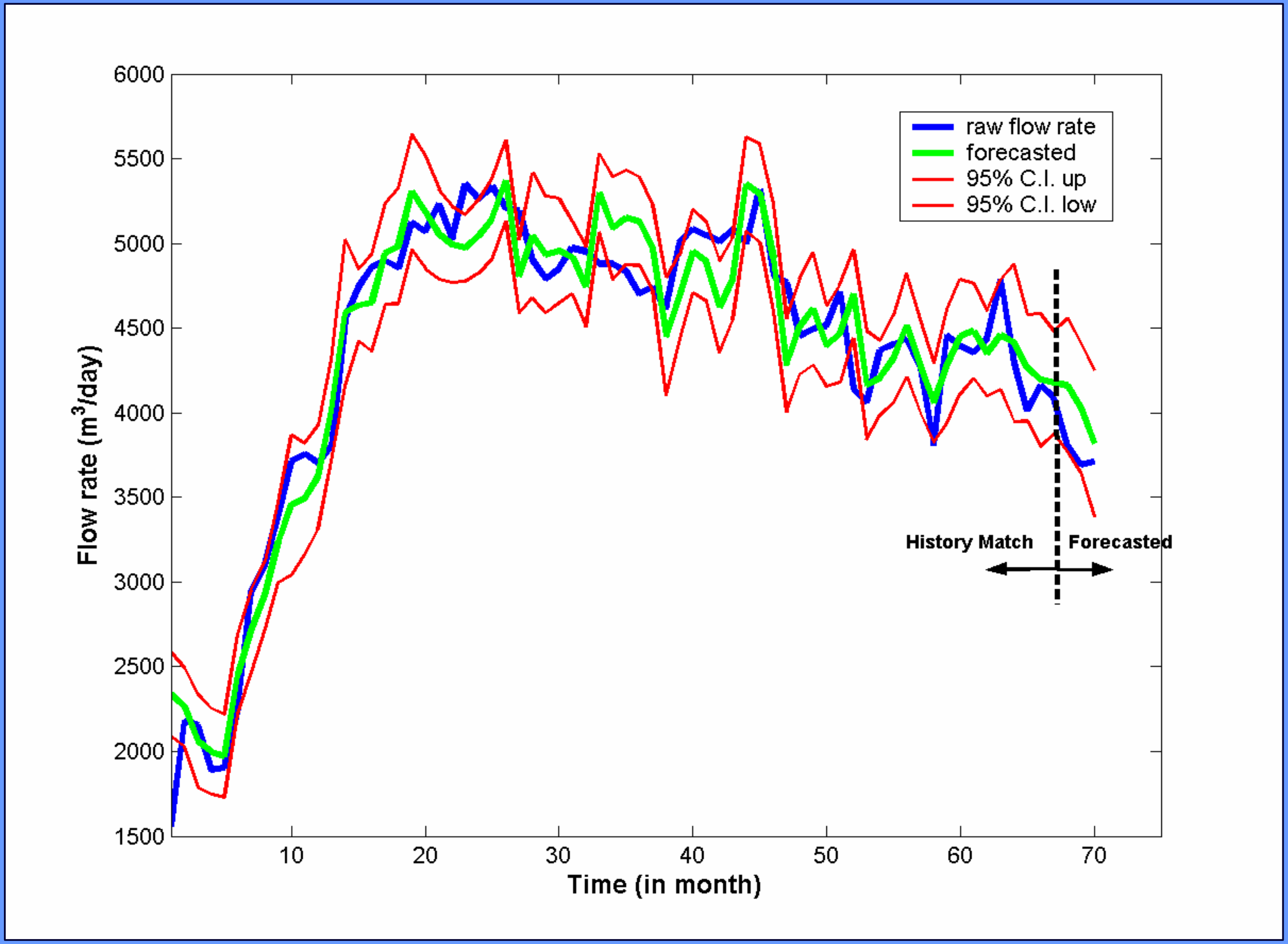
$\langle x \rangle \sim t^{0.3}$ for significantly correlated well pairs

$\langle x \rangle \sim t^{0.07}$ for earthquakes (Mw>=5.0) (Huc & Main, 2003)

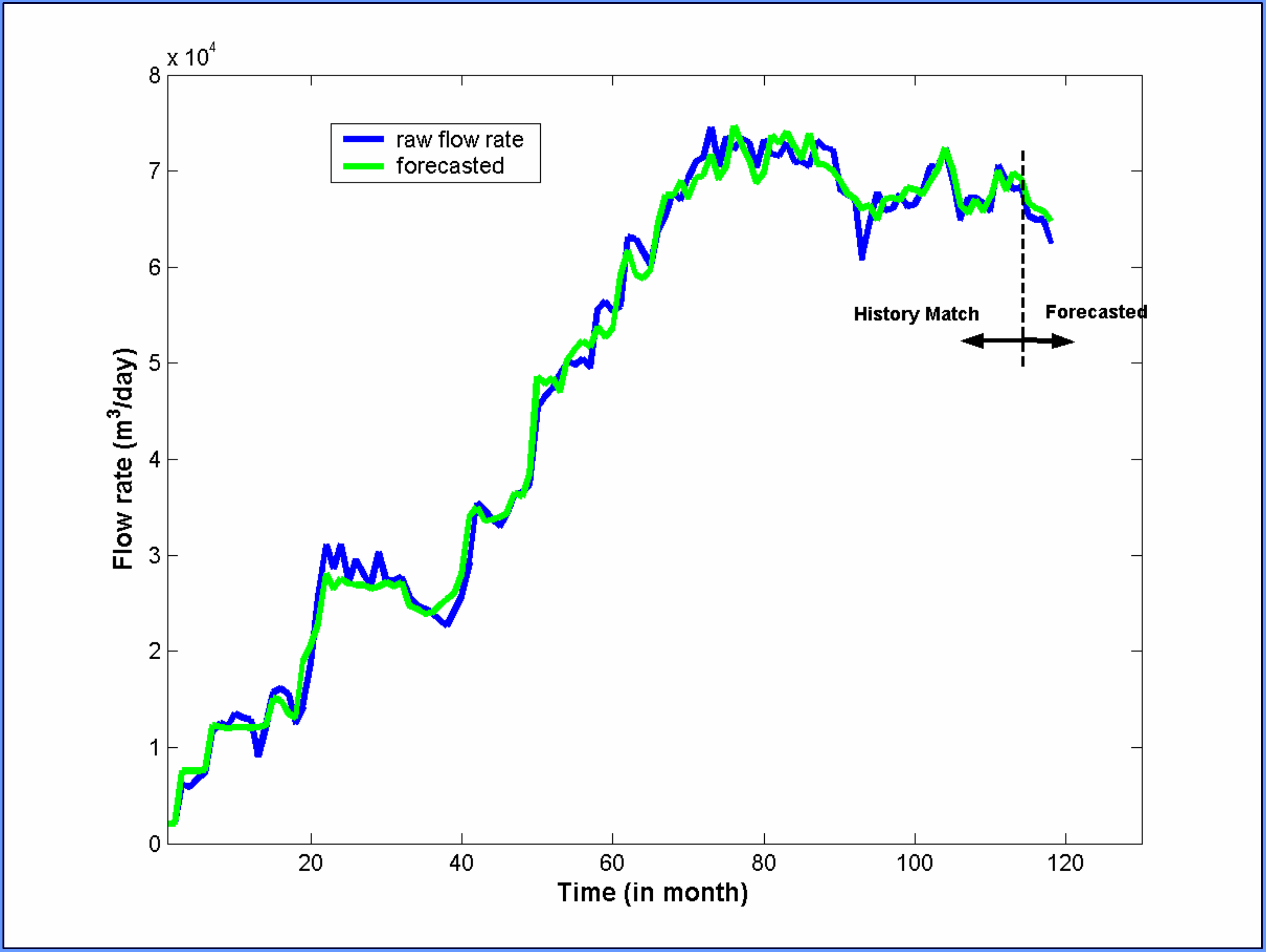
Principal component analysis



Predictive trial for a single well

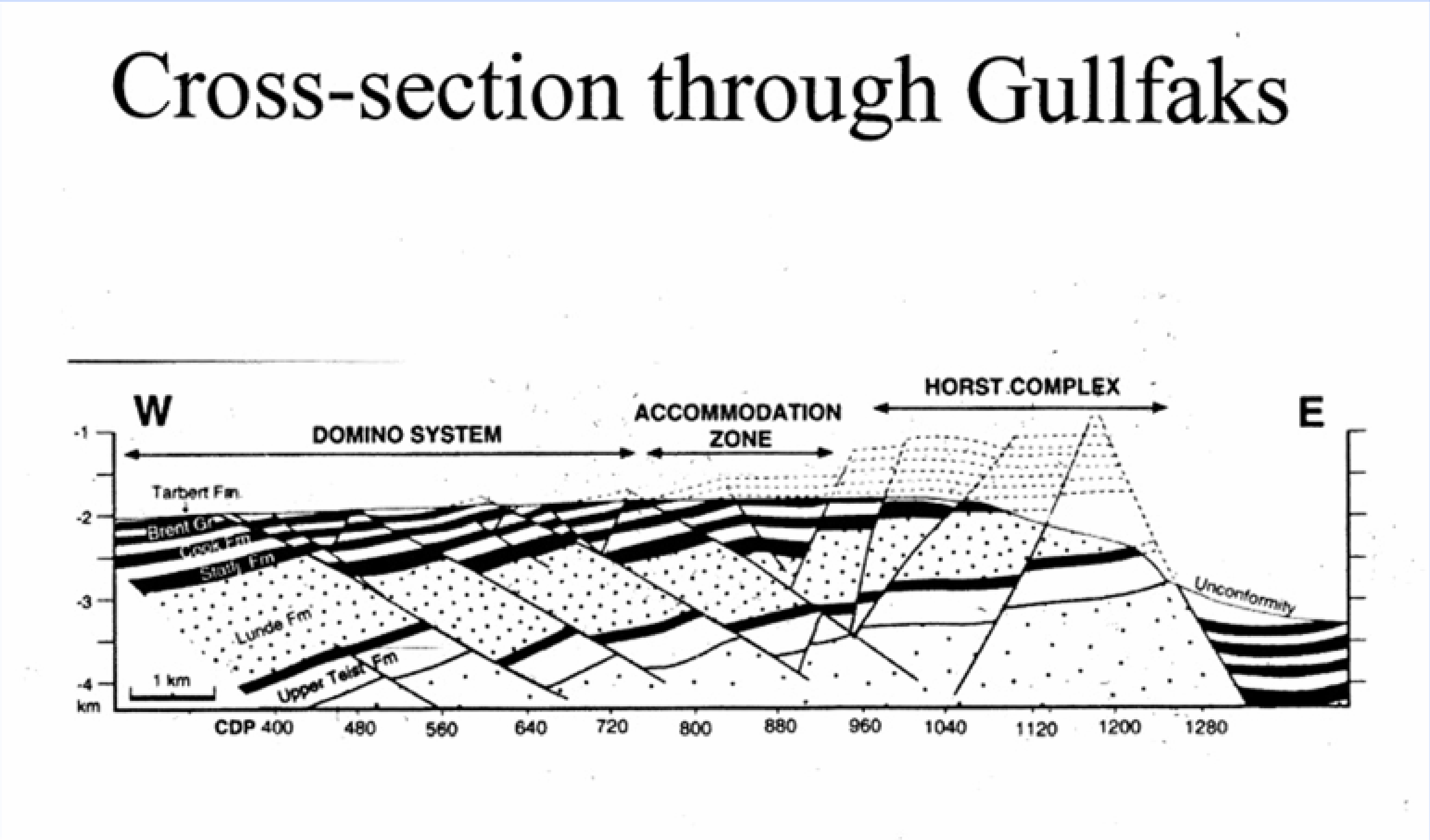


Predictive trial for a group of wells



Note good statistical averaging

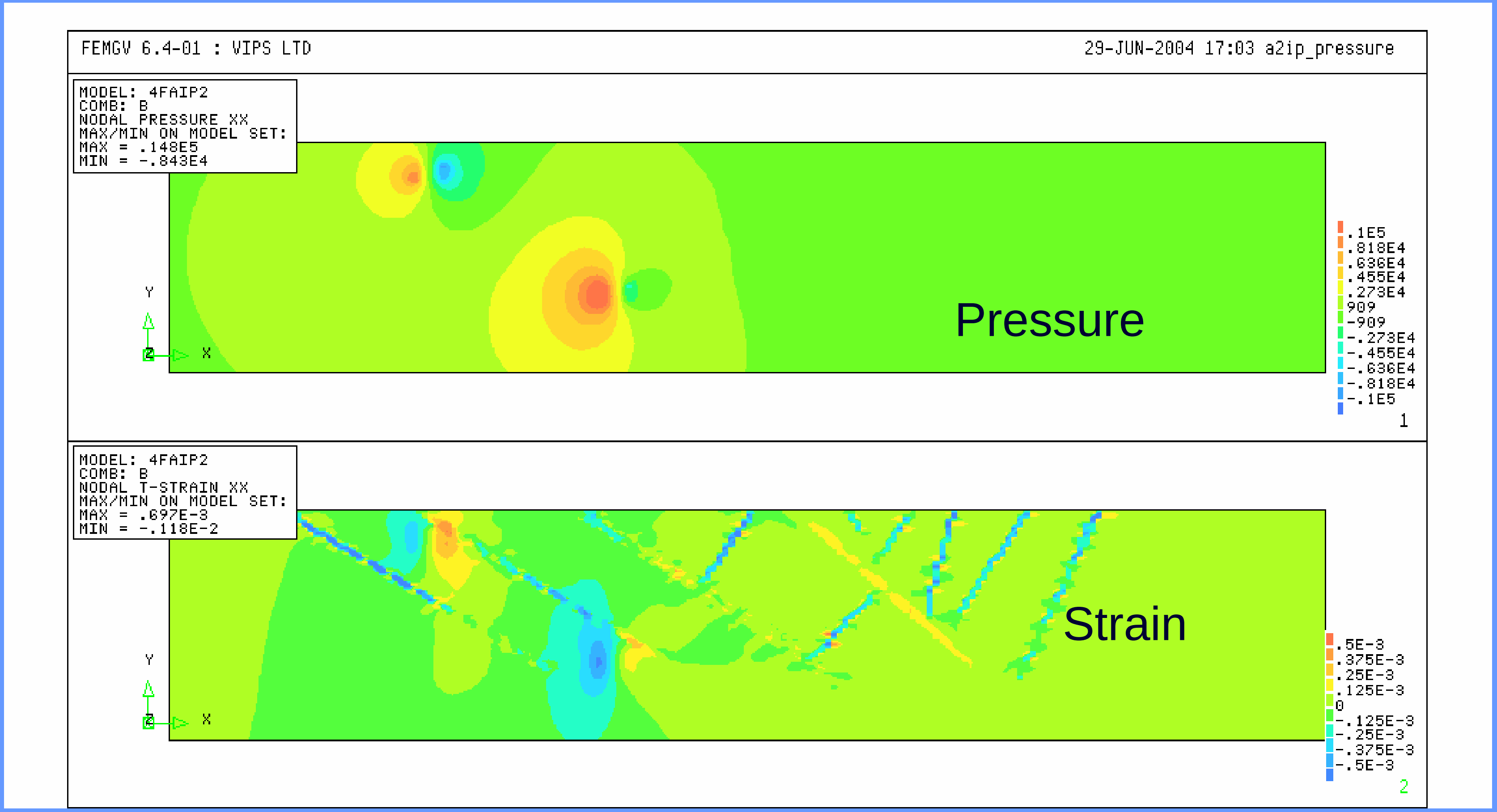
Geo-mechanical model: Reservoir architecture



Fossen & Hesthammer (1998) 2D cross section

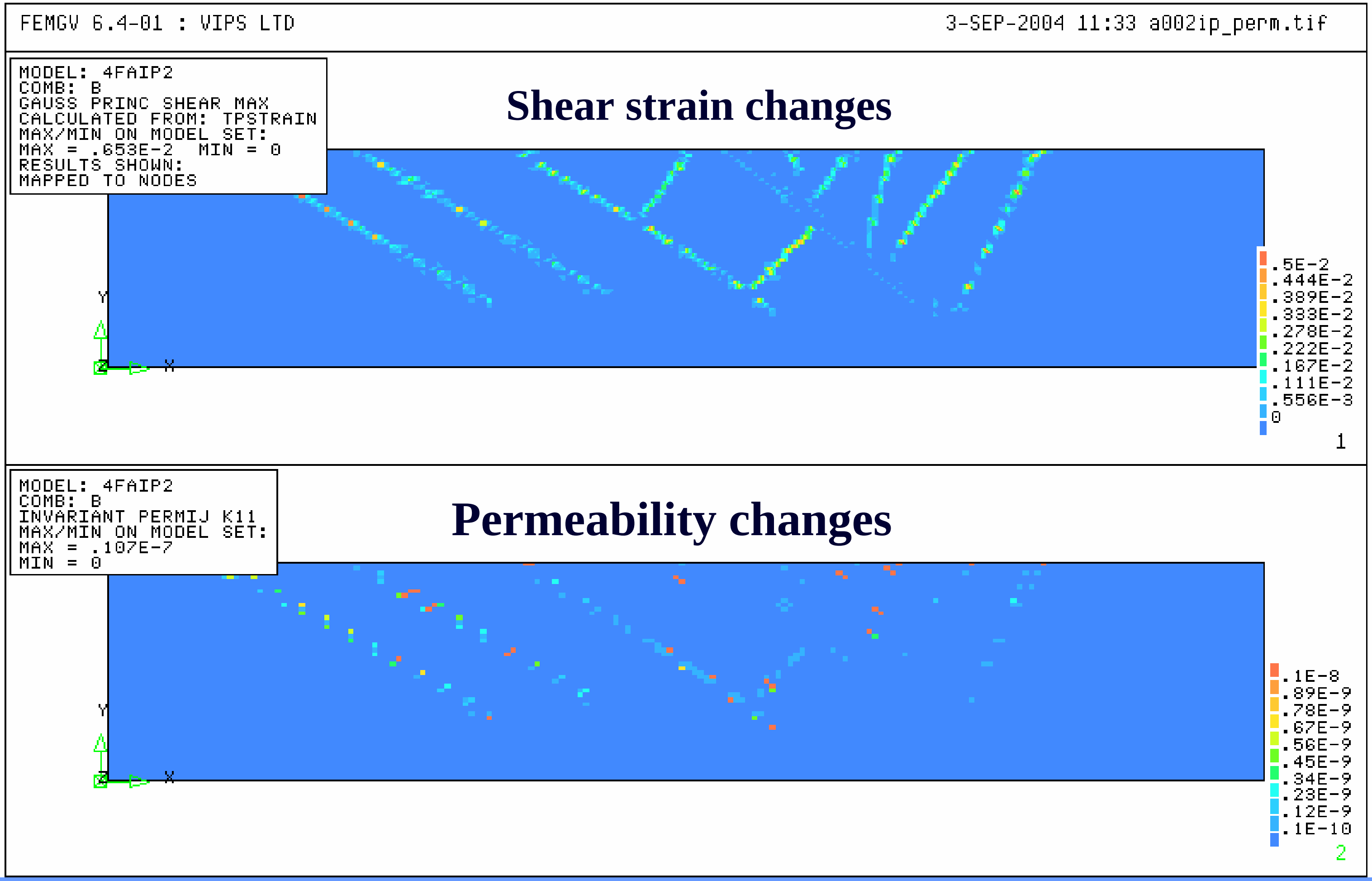
Geo-mechanical simulation

(2D model in cross section)



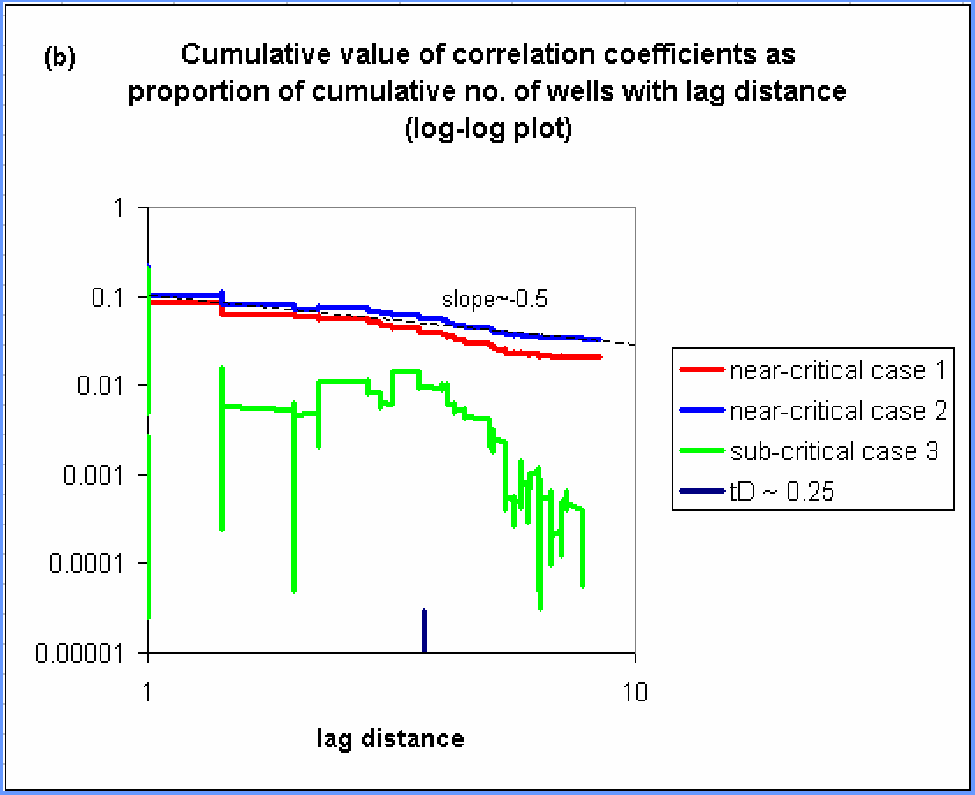
Pressure change and volumetric strain: critical case

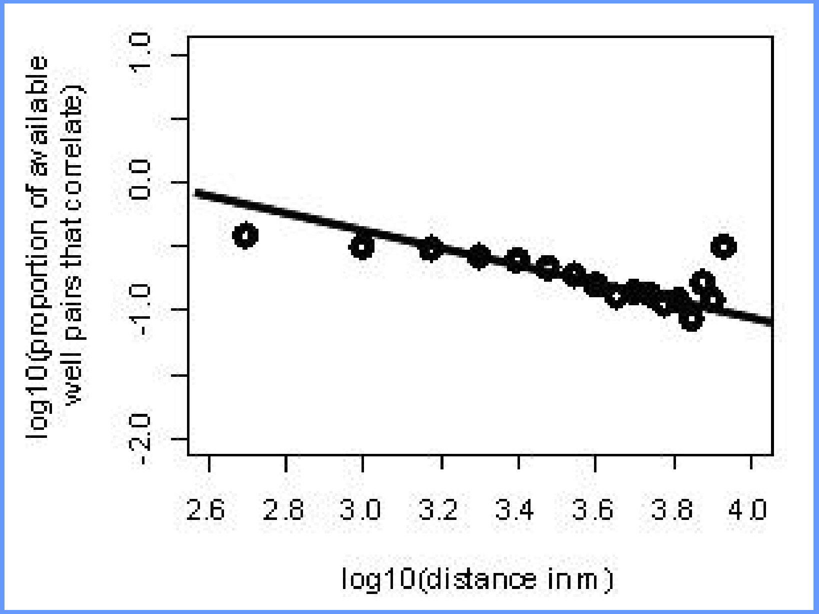
Geo-mechanical simulation



Geo-mechanical simulation

(2D model in plan view for a synthetic regular grid of wells)





c.f. data from Gullfaks

Schlumberger

Conclusion

- Oilfield flow rate correlations behave very similarly to earthquake-earthquake triggering
- The results agree with deterministic geo-mechanical simulations *iff* the system is critical
- The first principal component agrees with fault architecture
- Good short-term predictability
- Many potential applications

Next steps…

- Further field trials (DTI 'RESURGE' project)
  - more data welcome
- Calibration and interpretation of principal components
- Compare with induced seismicity response (independent validation of geo-mechanical simulations)
- Apply to earthquake-earthquake triggering (EU 'TRIGS' network)